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The objective of this Multidisciplinary University Research Inititative (MURI) program is to apply multivariable control, simulation, optimization and signal processing techniques to the microlithography sequence.

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Multivariable Control, Simulation, Optimization, and Signal Processing for the Microlithographic Process

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Final Report: August 1, 1995 -- June 30, 2001

A Multidisciplinary University Research Initiative Project of the Defense Advanced Research Projects Agency

Summary

The objective of this Multidisciplinary University Research Initiative (MURI) program is to apply multivariable control, simulation, optimization and signal processing techniques to the microlithography sequence (www-isl.stanford.edu/groups/MURI). This final report only summarizes the major contributions and highlights of our effort. More details can be obtained from our annual reports.

1. Research Highlights (Stanford University)

1.1 Design of Phase-Shifting Masks

We have developed algorithms for optical lithography that enable Moore's law to be advanced by several generations. They have demonstrated the (approximate) solution of a highly nonlinear inverse problem that enabled the automated design of phase-shifting masks (PSMs) for arbitrary layouts. Moreover their proof that all such masks could be implemented via two passes with just binary PSMs made their implementation feasible. For example, Motorola is using these ideas (via commercial grade software developed by a Stanford spinoff, Numerical Technologies, Inc.) to manufacture Power PC chips with smallest feature sizes of 110nm(.11 um) using current 248nm sources. In May 2000, MIT Lincoln Laboratory announced successful fabrication (albeit in a research rather than a production environment) of transistors with 25nm feature sizes again using current 248nm sources! Numerical Technologies had a successful IPO in April 2000 (see www.numeritech.com for more on the technology and the company).

1.2 Thermal Processing System

We have developed temperature control algorithms and patented gear for conducting the most thermally sensitive deep-ultraviolet lithography processes used in making the photomasks for sub-180 nm feature-size chips. This technology has been transferred through a licensing arrangement to a company APT Systems, which has transitioned it into a commercial-grade product. The first productized system was successfully delivered in July, 2000, to a major manufacturer of photomasks with several follow-on orders scheduled for delivery in 2001. The purpose of the technology is to place stringent controls on the photomask processing temperature trajectories, thereby enabling highly sensitive photoresists to manufacture advanced photomasks. The basis for the system was an analysis of the thermal characteristics of large volume substrates to show that nonuniform local heating was needed to achieve uniform heating at the substrate plane. Further analysis showed that decoupling the heating modes into independent rapidly responding units was required to achieve fast response times with minimal out-of-plane stress-induced deformation. The resulting technology is a major departure from conventional heating systems since it utilizes high dimensional multivariable spatial control to manipulate the temperature field over a small grid. The system is nearly two orders of magnitude faster than conventional equipment (response times of 20 seconds versus 2000 seconds) and provides an order of magnitude improvement in spatial controllability (625 mm^2 local heating fields versus 18,000 mm^2 fields). Further, the system provides an in-situ quench capability that had never been achieved in the industry. This adds-up to a system with extreme temperature control

capabilities, providing advantages in yield, throughput and across-substrate electronic performance. This precise method of temperature control may also find use in other areas, such as independently controlling all linear distortion modes for precision overlay. This enables multi-layer molecular-level contact printing on curved surfaces for fabrication of spherical infrared focal plane arrays that have application for ultra-high definition panoramic imaging systems. Other interests for the thermal array technology are in processing low-k dielectric materials, spin-on glass, processing thick photolabilie materials, copper annealing. Also, the bio area has expressed interest in using the thermal array for genotyping using bio-chips.

1.3 Micromachined Piezoelectrically Actuated Flextensional Transducers For High Resolution Fluid and Solid-Particle Deposition

There is a continuing need for alternative deposition techniques of organic polymers in precision droplet-based manufacturing and material synthesis, such as the deposition of photoresist without spinning on large or oddly shaped substrates. In this research, we present a technique for the deposition of inks, organic polymers, solid particles, fuels, biological and chemical fluids, using a fluid ejector. The ejector design is based on a flextensional transducer that excites the axisymmetric resonant modes of a clamped circular plate. It is constructed by depositing a thin piezoelectric annular plate onto a thin, edge clamped, circular plate. Liquids and solid-particles are placed behind one face of the plate which has a small orifice at its center. By applying an ac signal across the piezoelectric element, continuous or drop-on-demand ejection of fluids and solid-particles has been achieved. The ejected drop size ranges in diameter from 5 micrometers at 3.5 MHz to 150 micrometers at 7 kHz, the corresponding ejected drop volume ranges from 65 femtoliters to 1.5 nanoliters, and the corresponding flow rate ranges from 0.2 microliters per second to 10 microliters per second. The unique features of the device are that the fluid is not pressurized, the fluid container is chemically and biologically compatible with most fluids, and the vibrating plate contains the orifice as the ejection source. The device is manufactured by silicon surface micromachining and implemented in the form of two-dimensional arrays. Individual elements are made of thin silicon nitride membranes covered by a coating of piezoelectric zinc oxide. This technology has been transitioned to Hewlett-Packard in a licensing arrangement with Stanford's Office of Technology Licensing.

1.4 Molecular Transfer Lithography

Recently, we developed a new process for conducting lithography. We call it Molecular Transfer Lithography (MxL) whose aim is to remove lithography as the bottleneck of semiconductor manufacturing. MxL applies conventional optical exposure technology to image photosensitive material coated on a pure carrier, subsequent to an aligned inverted transfer of the resultant latent image to the wafer. The estimates for this approach are an improvement of the in-line throughput of stepper/scanner technology by a factor of 3-6 while significantly cutting the cost of the optical imaging tool. MxL works in conjunction with existing patterning/exposure tools to lower manufacturing and capital costs, while removing or reducing critical technical problems associated with imaging tools such as depth of focus, resolution, reflectivity and contamination. The applications include printing, Semiconductor Lithography for Manufacturing Integrated Circuits, Lithography on curved substrates, MEMS and biological patterning uses.

2. Research Highlights (Boston University)

2.1 Limitation of the Kirchhoff boundary conditions in 157-nm lithography - There is great current interest in pushing optical lithography to the 70-nm technology node by using an exposure wavelength of 157 nm. At this wavelength, the chromium absorber material in a photomask is less absorptive than at the wavelength of 248 nm or 193 nm currently used for manufacturing. As a result, the thickness of the chromium layer relative to the wavelength in a 157-nm photomask will have to be increased, leading to greater diffraction effects in the propagation of the light through the photomask apertures. The goal of this project is to assess the limitation of the approximate Kirchhoff boundary conditions in 157-nm lithography simulation, by comparing the Kirchhoff results with those obtained from rigorous finite-difference time-domain (FDTD) computation. It is found that the discrepancies between the Kirchhoff and FDTD results are much larger at 157 nm than at 248 nm in the case of TM polarization. This indicates that diffraction effects in the photomask apertures must be included when simulating aerial images in 157-nm lithography.

3. Personnel

Stanford University

Professor Thomas Kailath (Principal Investigator)

Professor Stephen Boyd

Professor Pierre Khuri-Yakub

Professor Fabian Pease

Professor Mark McCord

Professor Bo Wahlberg

Dr. Anders Hannson

Dr. Buno Pati

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Dr. Gurcan Aral

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Yaoting Wang

Harris Vikalo

Boston University

Prof. Eytan Barouch

Prof. Steven Orszag

Prof. Michael Yeung

Prof. Uwe Hollebach

So Yeon Baek

Zhen Wang

Xima Zhang

Ashish Sodhi

4. Ph.D. Dissertations

1. Yaoting Wang (Stanford 1997) *Automated design of phase-shifting masks for microlithography.*
2. Amir Ghazanfarian (Stanford 1999) *Subspace techniques for lithography in integrated circuit manufacturing.*
3. Susan Morton (Stanford 1999) *Ultrasonic sensor for photoresist process monitoring.*
4. Khalid El-Awady (Stanford 2000) *Programmable thermal processing module for semiconductor substrates.*
5. Gokhan Percin (Stanford 2000) *Micromachined piezoelectrically actuated flextensional transducers for high resolution fluid and solid-particle deposition.*

4 MURI Supported Publications - August 1996 - July 1997

4.1 Books (Stanford)

[1] A. Paulraj, V. Roychowdhury, C. Schaper, Eds., *Communications, Computation, Control and Signal Processing: A Tribute to Thomas Kailath*. Kluwer Publishers, Boston, 1997.

[2] B. Hassibi, A.H. Sayed and T. Kailath, *Indefinite Quadratic Estimation and Control: A Unified Approach to H^2 and H^∞ Theories*. SIAM Studies in Applied Mathematics, Philadelphia, PA, 1997.

4.2 Book Chapters (Stanford)

[3] T. Kailath, "Norbert Wiener and the Development of Mathematical Engineering," pp. 93-116 in D. Jerison, I. Singer, D. Stroock, Eds., *The Legacy of Norbert Wiener*, Amer. Math. Society, 1997.

[4] L. Vandenberghe and S. Boyd, "Connections Between Semi-Infinite and Semidefinite Programming", to appear in R. Reemtsen and J.-J. Rueckmann, Eds., *Semi-Infinite Programming*, Kluwer Publishers, 1997.

4.3 Book Chapters (BU/Princeton/Yale)

[5] S.A. Orszag, E. Barouch, U. Hollerbach, and R. Vallishayee, "Simulation of Microlithographic Processes", accepted, 1997.

4.4 Published/Accepted Journal Papers (Stanford)

[6] H. Liu, G. Xu, L. Tong, and T. Kailath, "Recent developments in blind channel equalization: from cyclostationarity to subspaces", *Signal Processing*, 50(1-2):83-99, 1996.

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[14] B. Hassibi. A.H. Sayed and T. Kailath. "Array Algorithms for H^∞ Estimation". To appear in *IEEE Transactions on Automatic Control*. 1997.

4.5 Published/Accepted Journal Papers (BU/Princeton/Yale)

[15] U. Hollerbach. "Effects of Aliasing Errors on Microlithographic Image Computations". *J. Sci. Comp.*. 1997

4.6 Submitted Journal Papers (Stanford)

[16] L. Vandenberghe. S. Boyd. and A. El Gamal. "Optimizing dominant time constants in RC circuits". submitted to *IEEE Transactions on Computer Aided Design*. 1996.

[17] M.S. Lobo. L. Vandenberghe. S. Boyd. and H. Lebret. "Second-order cone programming". submitted to *Linear Algebra and Applications*. 1997.

[18] K. El-Awady. C. Schaper. and T. Kailath. "Thermal Cycling Module for Photoresist Processing". submitted to *IEEE Trans. Semiconductor Manufacturing*. 1997.

[19] C. Schaper. T. Kailath. and Y. J. Lee. "Decentralized Control of Wafer Temperature for Rapid Thermal Processing Systems". submitted to *IEEE Trans. Semiconductor Manufacturing*. 1997.

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[21] G. Perçin. A. Atalar. F. L. Degertekin. and B. T. Khuri-Yakub. "Micromachined Two Dimensional Array Piezoelectrically Actuated Transducers." submitted to *Applied Physics Letters*. 1997.

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[27] Amir A. Ghazanfarian, Fabian W. Pease, Xun Chen, Mark A. McCord, "A new approach to global alignment in IC manufacturing baed on a neural network model", SPIE's 22nd Int'l symposium on microlithography, March 1997

[28] Amir A. Ghazanfarian, Fabian W. Pease, Xun Chen, Mark A. McCord, "A neural network model for global alignment incorporating wafer and stage distortion", The 41th Int'l conference on Electron, Ion, and Photon beam technology and nanofabrication, May 1997

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[31] B. Hassibi and T. Kailath, "Mixed least-mean-squares/H^∞-optimal adaptive filtering" In *Proceedings of the 30th Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, pp. 425-430, Nov. 1996.

[32] B. Hassibi and T. Kailath, "On Nonlinear Filters for Mixed H^2/H^∞ Estimation", Proceedings of the 1997 American Control Conference, Albequerque, NM, June 1997.

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[36] B. Hassibi and T. Kailath, "Tracking with an H^∞ Criterion", to appear in the *Proceedings of the 36th IEEE Conference on Decision and Control*, San Diego, CA, Dec. 1997.

[37] B Halder, B Hassibi and T. Kailath, "Linearly combined suboptimal mixed H^2/H^∞ controllers", to appear in the *Proceedings of the 36th IEEE Conference on Decision and Control*, San Diego, CA, Dec. 1997.

4.8 Published/Accepted Conference Papers (BU/Princeton/Yale)

[38] M. S. Yeung and E. Barouch, "Three-Dimensional Nonplanar Lithography Simulation using a Periodic Fast Multipole Method", *Proc. SPIE*, Vol. 3051, pp. 509-521, 1997.

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[43] A.Ronnekleiv, P.Roche, and B.T.Khuri-Yakub, "Analysis of micro machineable piezoelectrically driven one dimensional flexural transducers", submitted to *IEEE Ultrasonics Symposium*, 1997.

[44] Non-linear dynamics of bimorph flexural mode disc transducers - P.Roche and B.T.Khuri-Yakub, "Non-linear dynamics of bimorph flexural mode disc transducers", submitted to *IEEE Ultrasonics Symposium*, 1997.

[45] G. Perçin, H. T. Soh, and B. T. Khuri-Yakub, "Resist deposition without spinning by using novel inkjet technology and direct lithography for MEMS," submitted to *SPIE International Symposium on Microlithography*, 1997.

4.10 Dissertation Abstracts (Stanford)

Dissertation Abstract of YaoTing Wang

Automated Design of Phase-Shifting Masks for Microlithography, Stanford University, June, 1997 - Over the past few years the semiconductor industry has made a very strong push towards the use of optical enhancements to enable printing of features beyond the resolution limits of diffraction-limited lithographic projection systems. It is generally agreed that advanced mask technologies such as optical proximity correct (OPC) and phase-shifting masks (PSM's) are needed. Both of these techniques require the development of fast automated design algorithms, for transition from process research and development to production manufacturing use.

In this thesis we describe a computationally efficient mask design algorithm based on alternating projection methods. We first develop the optimal coherent decomposition (OCD) method to approximate complicated partially coherent systems with simple coherent systems. Then, we cast the mask design problem as a classical phase-retrieval problem in optics, and construct a close relative of the well-known Gerchberg-Saxton algorithm to design masks for arbitrary IC patterns. To control mask complexity, we propose a double-exposure strategy that produces a desired pattern by exposing two simple two-phase masks sequentially, and the half-toning methods that enable closer approximations to continuous modulation of amplitude by the mask.

The algorithm described in this thesis has been experimentally verified using a variety of test patterns ranging from simple u-shaped patterns to more complex gate-array and SRAM patterns.

Dissertation Abstract of Paul Dankoski

Multivariable Control of a Rapid Thermal Processor Using Ultrasonic Sensors. Stanford University, June, 1997 - The semiconductor manufacturing industry faces the need for tighter control of thermal budget and process variations as circuit feature sizes decrease. Strategies to meet this need include supervisory control, run-to-run control, and real-time feedback control. Typically, the level of control chosen depends upon the actuation and sensing available.

Rapid Thermal Processing (RTP) is one step of the manufacturing cycle requiring precise temperature control and hence real-time feedback control. At the outset of this research, the primary ingredient lacking from in-situ RTP temperature control was a suitable sensor. This research looks at an alternative to the traditional approach of pyrometry, which is limited by the unknown and possibly time-varying wafer emissivity. The technique is based upon the temperature dependence of the propagation time of an acoustic wave in the wafer.

The aim of this thesis is to evaluate the ultrasonic sensors as a potentially viable sensor for control in RTP. To do this, an experimental implementation was developed at the Center for Integrated Systems. Because of the difficulty in applying a known temperature standard in an RTP environment, calibration to absolute temperature is nontrivial. Given reference propagation delays, multivariable model-based feedback control is applied to the system. The modelling and implementation details are described. The control techniques have been applied to a number of research processes including rapid thermal annealing and rapid thermal crystallization of thin silicon films on quartz/glass substrates.

Dissertation Abstract of Babak Hassibi

Indefinite Metric Spaces in Estimation, Control and Adaptive Filtering. Stanford University, June, 1997 - The goal of this thesis is two-fold: first, to present a unified mathematical framework (based upon optimization in indefinite metric spaces) for a wide range of problems in estimation and control, and second, to study the implications of robust estimation and control to the area of adaptive signal processing.

Robust estimation (and control) is concerned with the design of estimators (and controllers) that have acceptable performance in the face of model uncertainties and lack of statistical information, and can be considered an outgrowth and extension of LQG theory, which assumed perfect models and complete statistical knowledge. One method of addressing the above problem is the so-called H^∞ approach, introduced by G. Zames in 1980, that has been recently solved by various authors.

Despite the "fundamental differences" between the philosophies of the H^∞ and LQG approaches to control and estimation, there are striking "formal similarities" between the controllers and estimators obtained from these two methodologies. In an attempt to explain these similarities, we shall describe a new approach to H^∞ estimation (and control), different from the existing (e.g., interpolation-theoretic-based, game-theoretic-based, etc.) approaches, that is based upon setting up estimation (and control) problems, not in the usual Hilbert space of random variables, but in an indefinite (so-called Krein) space.

The Krein space formulation unifies the treatments of LQG, H^∞, risk-sensitive, and game-theoretic,

estimation and control, and allows one to use the insight obtained from over three decades of work in traditional LQG theory to obtain new results in these other areas. Proceeding in this spirit, we demonstrate how to generalize the numerically superior square-root, and the fast Chandrasekhar, algorithms to the H^∞ setting, and embark on some new investigations on the asymptotic behaviour of H^∞ solutions, and on the existence and properties of solutions of (possibly) indefinite algebraic Riccati equations.

We also apply the H^∞ approach to adaptive filtering and show that the celebrated LMS (least-mean-squares) adaptive algorithm is H^∞-optimal. This result solves the long standing issue of finding a rigorous basis for LMS (which was long regarded as an approximate least-squares solution) and suggests further ramifications, some of which are described.

5 Interactions/Transitions

5.1 Interactions (Stanford)

- Applied Materials - option to license two technologies: collaborative investigations on future developments: a student has taken a leave of absence from the university to work with them
- CVC Products - implemented and commercialized decentralized control strategy for wafer temperature control on rapid thermal chemical vapor deposition module
- E-TECH - cooperative research on developed thermal cycler for photoresist processing on thick quartz glass used for masks: donated equipment and provided test data on the performance of our technology
- Hewlett-Packard - built and tested a phase-shifting masks designed by us
- IBM - collaborating on project attempting to uniformly process photoresist on x-ray mask membranes; have donated equipment
- KLA - supported a summer student working on fault detection problems in IC manufacturing
- National Semiconductor - discussions on testing of the photoresist thermal processing technology
- Numerical Technologies - pursued extensions and productization of our research on model-based aerial imaging systems and phase-shifting mask design.
- SEMATECH (factory automation group) - discussions on commercialization of thermal processing technology
- SEMATECH (mask strategy group) - discussions on the application of thermal processing technology for photoresist on 9" quartz reticles
- Silicon Valley Group - supported a summer student working on problems in alignment
- Texas Instruments - supported one years research for a graduate student in our microlithography group
- Ultratech Stepper - participated in the implementation of our stepper alignment strategy

4 MURI Supported Publications - August 1997 - July 1998

4.1 Books (Stanford)

[1] B. Hassibi, A.H. Sayed and T. Kailath. *Indefinite Quadratic Estimation and Control: A Unified Approach to H^2 and H^∞ Theories.* SIAM Studies in Applied Mathematics. Philadelphia. PA. 1998.

4.2 Book Chapters (Stanford)

[2] L. Vandenberghe and S. Boyd. "Connections Between Semi-Infinite and Semidefinite Programming", to appear in R. Reemtsen and J.-J. Rueckmann. Eds., *Semi-Infinite Programming.* Kluwer Publishers, 1997.

[3] S. Boyd. Entropy and random feedback. In V. Blondel. E. Sontag. M. Vidyasagar. and J. Willems, editors. *Open Problems in Mathematical Systems Theory and Control.* Springer-Verlag, 1998.

4.3 Book Chapters (BU/Princeton/Yale)

[4] S.A. Orszag. E. Barouch, U. Hollerbach, and R. Vallishayee. "Simulation of Microlithographic Processes", accepted. 1997.

4.4 Published/Accepted Journal Papers (Stanford)

[5] G. Perçin. T. S. Lundgren. and B. T. Khuri-Yakub. "Controlled ink-jet printing and deposition of organic polymers and solid-particles," in *Applied Physics Letters*, vol. **73**, no. 16, (in press), 19 October 1998.

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[8] Susan L. Morton. F. Levent Degertekin. B.T. Khuri-Yakub, "In Situ Monitoring of Photoresist Development," to appear *Applied Physics Letters*, October 12, 1998.

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[15] C. Schaper, T. Kailath, and Y. J. Lee, "Decentralized Control of Wafer Temperature for Rapid Thermal Processing Systems", submitted to *IEEE Trans. Semiconductor Manufacturing*, 1997.

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[18] E. Rimon and S. P. Boyd. Obstacle collision detection using best ellipsoid fit. *Journal of Intelligent and Robotic Systems*, 18:105–126, 1997.

4.5 Published/Accepted Journal Papers (BU/Princeton/Yale)

[19] U. Hollerbach, "Effects of Aliasing Errors on Microlithographic Image Computations", J. Sci. Comp., Vol. 12, pp. 3-10 (1997).

[20] R. Vallishayee, S. Orszag, E. Jackson and E. Barouch, "Manufacturability of Electronic Chips", Theoretical and Computational Fluid Dynamics, Vol. 10, pp. 407-424 (1998).

4.6 Submitted Journal Papers (Stanford)

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5 Interactions/Transitions

5.1 Interactions (Stanford)

- Applied Materials - option to license two technologies: collaborative investigations on future developments; a student has taken a leave of absence from the university to work with them
- CVC Products - implemented and commercialized decentralized control strategy for wafer temperature control on rapid thermal chemical vapor deposition module
- E-TECH - cooperative research on developed thermal cycler for photoresist processing on thick quartz glass used for masks; donated equipment and provided test data on the performance of our technology
- Hewlett-Packard - built and tested a phase-shifting masks designed by us
- KLA - supported a summer student working on fault detection problems in IC manufacturing
- Numerical Technologies - pursued extensions and productization of our research on model-based aerial imaging systems and phase-shifting mask design.
- Silicon Valley Group - supported a summer student working on problems in alignment

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1. G. Percin and B. T. Khuri-Yakub, ``Micromachined piezoelectrically actuated flextensional transducers for high resolution printing," IS&T's NIP16: International Conference on Digital Printing Technologies, October 15-20, 2000, Vancouver, B.C., Canada.

2. G. Percin and B. T. Khuri-Yakub, ``Plate equations and equivalent circuit for piezoelectrically actuated flextensional transducers," ISAF 2000: 12th IEEE International Symposium on the Applications of Ferroelectrics, July 30 - August 2, 2000, Honolulu, Hawaii.

3. G. Percin and B. T. Khuri-Yakub, ``Plate equations and equivalent circuit for micromachined piezoelectrically actuated flextensional transducers," 139th Meeting of the Acoustical Society of America, May 30 - June 3, 2000, Atlanta, Georgia.

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